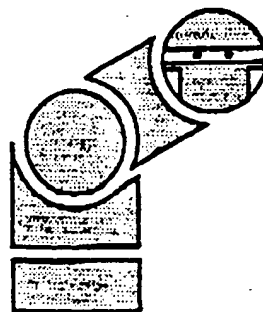


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Robotic Manipulator for Endoscopic Handling of Surgical Effectors and Cameras

B. Neisius, P. Dautzenberg, R. Trapp

Kernforschungszentrum Karlsruhe GmbH, Hauptabteilung Ingenieurtechnik (HIT)
Postfach 3640, D-76021 Karlsruhe, Germany

in cooperation with

Prof. G.Bueß
Department of General Surgery, University of Tübingen
Hoppe-Seyler-Str. 3, D-72076 Tübingen, Germany

Abstract: In this paper a design concept of a tele-manipulator for laparoscopic surgery is presented. It enables precise handling of surgical effectors and cameras inside the abdominal cavity with six degrees of freedom of motion through a trocar tube less than 15 mm in diameter. The kinematical structure consists of fifteen axes articulated by six electrical servo drives.

The corresponding manipulator system consists of a powered, dexterous instrument and an instrument guiding system. The latter enables safe and precise rotation of the instrument shaft around an invariant point in the abdominal wall. A special joy-stick with the same kinematical structure will be employed as a first device for motion control in master-slave-mode.

1 Introduction

No other surgical technique has revolutionized abdominal surgery so much as endoscopic surgery did. Through trocar tubes in the abdominal wall slim rigid instruments are moved to the location of interest to the surgeon. Organs and tissue are treated with a variety of effectors. The rigid instrumentation is simple and allows appendix- and gall bladder surgery to be performed. Especially in abdominal surgery these endoscopic procedures compete with the conventional techniques of open surgery. More complex endoscopic operations are right now the subject of intensive surgical research.

The surgeon applying endoscopic techniques must cope with a number of disadvantages:

- Direct, three-dimensional view is no longer possible.
- Rigid instruments restrict the dexterity of surgical effectors.
- Work with conventional instruments and the required precision imply a high physical stress for the surgeon.

First stereoscopic cameras are already used in endoscopic surgery, but currently employed instruments are still

restricting the surgeon's capabilities during more complex endoscopic procedures. Special devices and systems for telemanipulated endoscopic handling of surgical effectors are still not available.

The requirements of endoscopic surgery [Bueß 88][Cuscheri 92] and the associated handling problems are very similar to those in remote handling technology in hostile environments. Under a project of cooperation with the University of Tübingen, endoscopic instruments with additional motion axes and combined surgical effector functions have been developed at Kernforschungszentrum Karlsruhe GmbH. Starting from the experience with steerable [Dautzenberg 92] and powered, dexterous instruments [Neisius 93], the development of a telemanipulator for laparoscopy [Rininsland 93] was launched.

2 Motivation

The goal of the concept presented is telemanipulated, endoscopic handling of different surgical effectors or cameras with six degrees of freedom of motion. This enables dexterous positioning at and orientation of the effectors to the organ structures in question with higher precision and improved ergonomics. The experimental robotic manipulator required consists of an instrument guiding system and exchangeable, endoscopic instruments with combined surgical effector functions. The following essential improvements of endoscopic handling technology have to be achieved:

- Endoscopic handling of surgical effectors with six degrees of freedom
- Larger working space and augmented dexterity
- Steady and safe instrument guiding around the incision point in the abdominal wall
- Motion control of the effector in effector coordinates
- Support for the surgeon by better ergonomics
- Higher precision during long procedures

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Considering that surgical effectors must be manipulated in complex, unstructured working environments like the abdominal cavity, a master-slave-mode of control is suggested. Motion control and path planning for the effector are done by the operator's hand in effector coordinates with a kind of joy-stick, the master-manipulator. The slave-manipulator positions and orientates the effector in the same manner indicated by the operator's hand movements. Thus, after a short learning phase quick and save telemanipulation can be established under improved ergonomical conditions. In a first step reflexion of the resulting handling forces on the master device is not absolutely necessary.

3 Kinematics of Endoscopic Handling

The kinematical scheme for an endoscopic manipulator results from the desired working space and the required motions of manipulator tip or effector. In laparoscopy the most important restriction of the working space is the interface of robotic manipulator and abdominal wall. At the beginning of an endoscopic operation the abdominal cavity is pressurized by insufflating CO_2 -gas in order to lift the abdominal wall and thus creating sufficient working space. Trocar tubes are then inserted into the abdominal wall. Through these ports the instruments will be moved towards the location of surgical intervention.

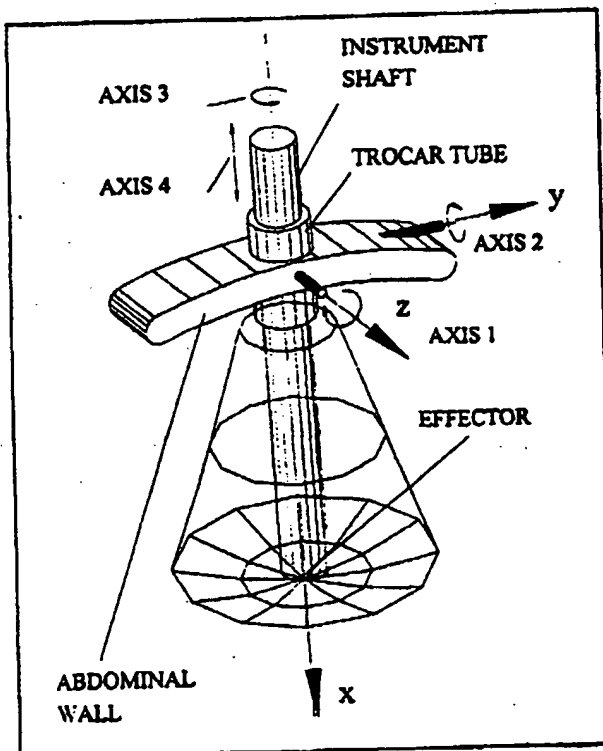


Fig. 1: Endoscopic kinematics of a rigid instrument.

If we consider the point of incision as invariant, the abdominal wall forms an elastic, cardanic suspension of the trocar tube, providing two axes of rotation 1 and 2 (Fig. 1). The endoscopic shaft of an instrument can be rotated and translated in the trocar tube around its longitudinal axis. These four degrees of freedom of motion do not allow safe travelling around organs and optimal orientation of surgical effectors.

In order to be able to manage more complex procedures of endoscopic handling and to improve the interaction of effector and environment, at least two additional degrees of freedom are required for effector orientation. They have been provided by a special endoscopic multi-link structure and a flexible shaft for effector rotation. The corresponding kinematical scheme of the Karlsruhe approach to endoscopic manipulator design is shown in Fig. 2.

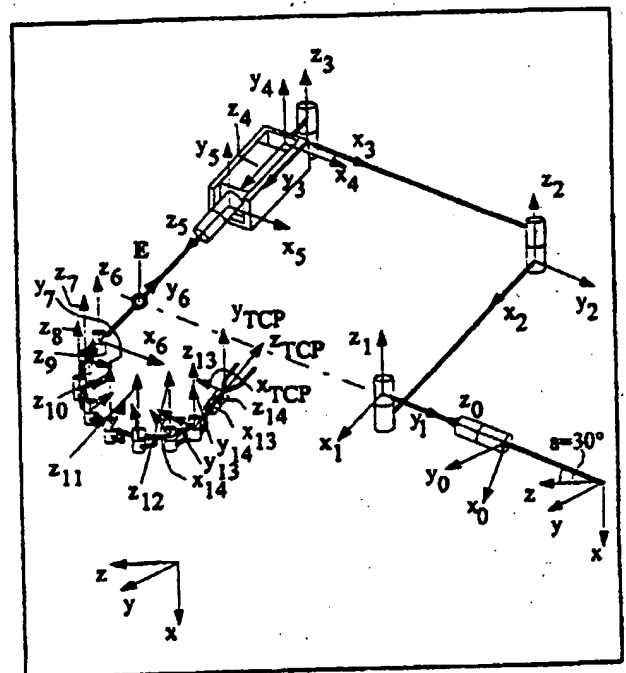


Fig. 2: Kinematical concept of flexible, endoscopic handling

The first motion axis z_0 is rotated by an angle of 30° around the y -axis of the base frame x, y, z . The corresponding rotation φ_1 around z_0 is driven by a geared dc-servo-motor. The rotations $\varphi_2, \varphi_3, \varphi_4$ about the axes z_1, z_2, z_3 are coupled by mechanical transmissions and driven by only one geared dc-servo-motor. Respecting the constraints of motions $\varphi_3 = \pi/2 - \varphi_2$ and $\varphi_4 = \varphi_2$ the axis z_4 intersects axis z_0 in a remote center of motion E. Thus, the cardanic suspension of the trocar tube at the point of incision in the abdominal wall is guaranteed. The instrument is subjected to a sliding motion d_5 along axis z_4 and a rotation φ_6 around axis z_5 . The endoscopic multi-link structure provides eight coupled axes from z_6, z_7, z_8 to z_{13} . The corresponding joint angles from $\varphi_7, \varphi_8, \dots, \varphi_{14}$ are all

equal due to linear coupling between the links of the structure. The planar swivel motion of this multi-link structure is driven by a single dc-servo-motor and is considered as one hybrid axis. Finally, the effector can be rotated by an angle ϕ_{15} around axis z_{14} by a flexible shaft. The kinematical structure presented has fifteen joint axes. Only six joint variables are independent. This concept provides six degrees of freedom for flexible effector positioning and orientation in the abdominal cavity respecting the point of incision in the abdominal wall.

The following ranges of motion have been proved by experiments with a prototype of the powered, dexterous instrument and by relevant computer simulations:

- $\phi_1 = \pm 90^\circ$ rotation around the incision point
- $\phi_2 = \pm 60^\circ$ rotation around the incision point
- $\phi_3 = \pi/2 - \phi_2$ mechanically coupled motion
- and $\phi_4 = \phi_2$
- $d_5 = 0-370 \text{ mm}$ translation of the instrument
- $\phi_6 = \pm 180^\circ$ rotation of the instrument's shaft
- $\phi_7 = \pm 22.5^\circ$ swiveling of the multi-link structure
- $\phi_7 = \phi_8 =$ mechanically coupled motion
- $\phi_9 = \dots = \phi_{14}$
- $\phi_{15} = \pm 180^\circ$ rotation of the surgical effector

The desired effector orientations are only feasible with certain arm configurations. Small, lateral motions of the abdominal wall around the remote center of motion are considered negligible because of its elasticity.

4 Design Concept

4.1 Powered Dexterous Instrument

The powered dexterous instrument consists of a surgical effector, the endoscopic multi-link structure, the instrument shaft as well as the drive unit (Fig. 3).

Miniaturized servo drives with planetary gears in the drive unit control the 'effector rotation' and 'swiveling of the multi-link structure' motions as well as the effector functions, e.g. grasping, cutting, and coagulating. The functions can be operated either by a set of keys on the instrument or by the master control device. To allow several instrument shafts with different combinations of effector functions to be used, a mechanical quick-change interface has been developed. In case of complete failure of all electric drives, the shaft of the instrument can be disconnected from the drive unit by the quick-change interface.

For efficient cleaning and sterilization the instrument's shaft can be taken apart quickly and easily. It does not contain sensors or actuators which would hardly survive sterilization.

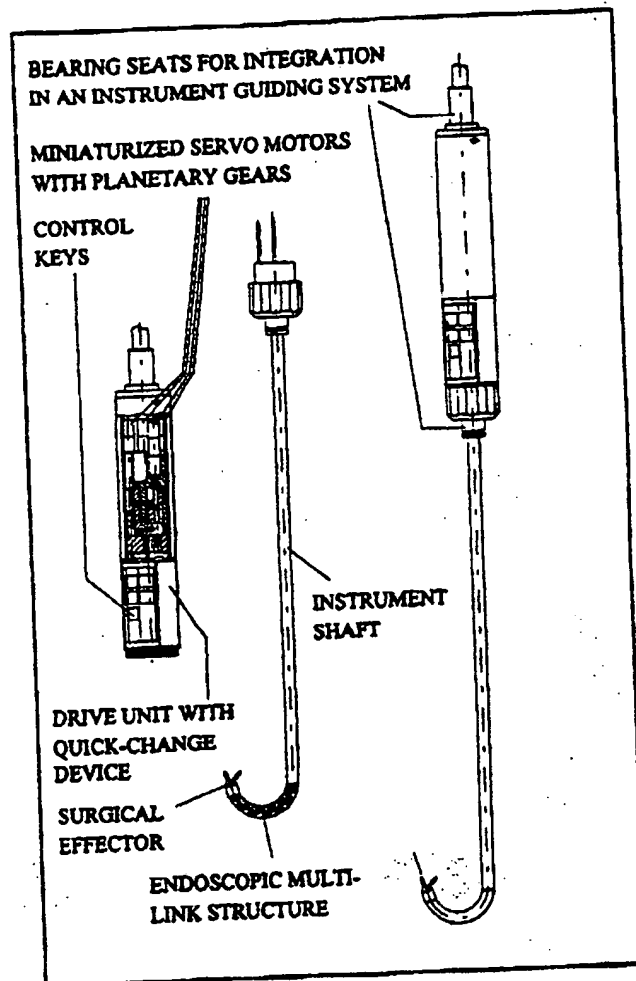


Fig. 3: Powered, dexterous instrument for the integration in an instrument guiding system

4.2 Surgical Effectors

In addition to simple grippers and scissors, effectors with combined surgical functions will be essential components of a robotic manipulator for endoscopic handling. The effectors described below have been developed from rigid instruments [Dautzenberg 93]. But they have to be adjusted to the powered instrument and the robotic manipulator system in such a way that tools can be changed safely and quickly.

4.2.1 Dissection and Preparation

Dissection and preparation of anatomical structures imply aspiration, irrigation, coagulation and cutting. These basic

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functions should be suitably combined in a single effector of an instrument. Changing the instruments during an operation is not only time consuming and inconvenient, but also dangerous to the patient. If unexpected bleeding occurs, the localization and control of the source without a multifunctional instrument is too slow. In order to simplify coagulation and cutting of vessel containing structures, several combination instruments have been developed in close cooperation with the Department of General Surgery of the University of Tübingen. One product of development is a bipolar forceps with completely insulated, U-shaped electrodes, semi-automatic cutting function and an irrigation and suction channel (Fig. 4). A new prototype, which can be completely disassembled, was tested successfully. This design guarantees an efficient cleaning and sterilisation.

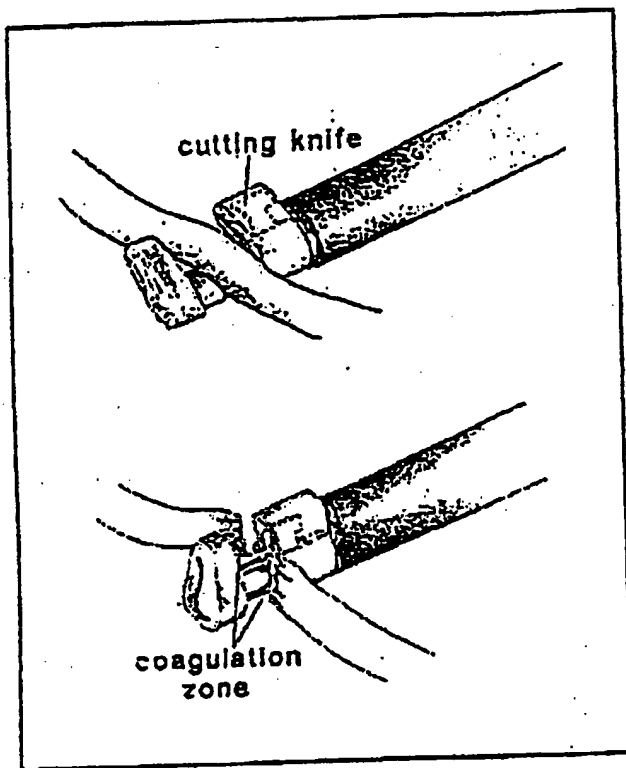


Figure 4: Drawing of a multifunctional bipolar coagulation forceps with integrated cutting, suction and rinsing device [Cuscheri 92],[Melzer 93]

4.2.2 Suturing

In advanced endoscopic surgery continuous and interrupted suturing is performed routinely, but nevertheless handicapped by difficulties in handling of the needle and thread.

A new "T-needle", operated by a pneumatically controlled sewing instrument, has been designed to simplify the endoscopic suturing technique and to create a semi-

automatic system suited as an effector of the endoscopic handling system. The "T-needle" has a central cross-bore for the thread and cone shaped, sharp tips on each side (Fig. 5). It can be moved back and forth between two clamps by alternately gripping the needle's tip with two opposing attachments integrated in the jaws.

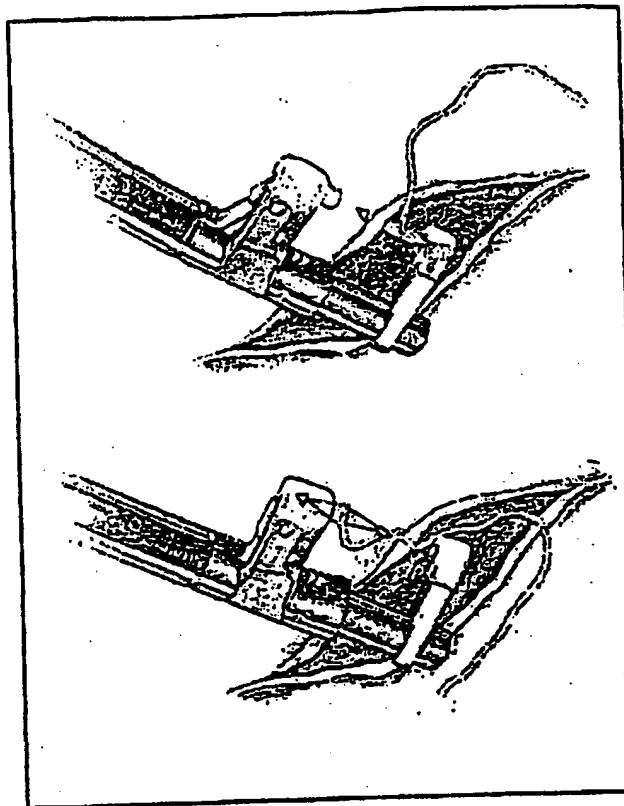


Figure 5: Drawing of the pneumatically controlled sewing instrument [Melzer 93].

This is achieved by foot controlled and pneumatically driven clamp unit in the fixed jaw versus a spring-loaded-clamp placed in the moveable jaw. When the former is activated, the T-needle is fixed and upon release the spring loaded clamp unit holds the needle. Different cross sections, shapes and directions of movement have been designed.

The needle moving device has been developed to improve the endoscopic suturing technique. The needle can be easily handled between both actuated clamps like in a weaving loom. Thus, making continuous sutures can be accelerated and simplified and the same is true for making knots.

The effectors were tested successfully in experiments involving both phantom and animal experiments at the University of Tübingen, Department of General Surgery. A new design focuses on efficient cleaning and sterilization. Further investigations into the quality of cleaning and sterilization will be carried out by experiments at the University of Tübingen. In standardized test procedures the

effectors will be contaminated with a radioactively labeled liquid. After cleaning and sterilization they will be examined with a gamma camera to detect any residual contamination [Roth 94].

The effectors will then be adapted to the powered, dexterous instrument, which is moved by an instrument guiding system around the point of incision in the abdominal wall.

4.3 Instrument Guiding System

By means of a manually operated quick-change device the powered, dexterous instrument is attached to the carrier of the instrument guiding system for translation and rotation around the longitudinal axis (Fig. 6). In the same way a flexible endoscope with electrically driven bending section can be inserted in the guiding system.

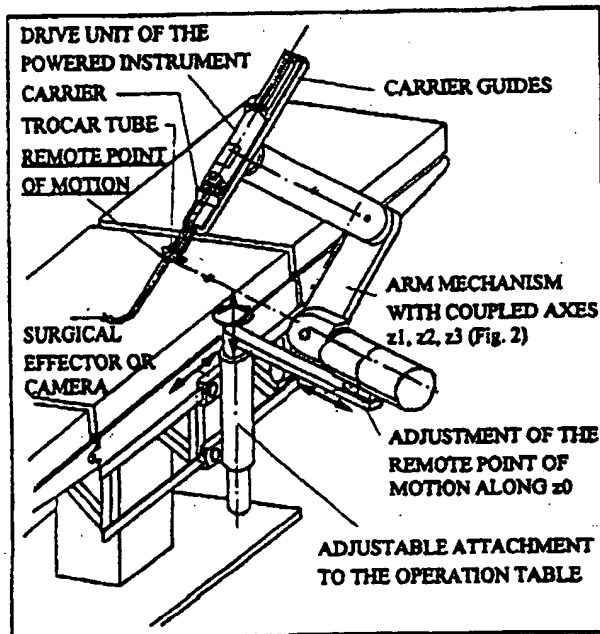


Fig. 6: Endoscopic slave-manipulator, consisting of the powered, dexterous instrument and the instrument guiding system

At the lower end of the carrier guides a trocar clamping mechanism is located to guarantee the alignment of the longitudinal axes of trocar tube and instrument. For safe and precise motion around the point of incision, a spherical mechanism is used which consists of an arm mechanism with the coupled axes z_1 , z_2 , z_3 and an axis of rotation z_0 of (Fig. 2). This articulated arm structure with two cardanic motion axes provides inherent safety through mechanical constraints. The design concept allows the invariant point of spherical mechanism to be adjusted to the abdominal wall by three additional translation axes indicated in Fig. 6. The base housing can be translated parallel to the inclined

rotation axis z_0 . The perpendicular support guide can be moved out of the support mounted on the operation table. The third axis of adjustment is provided by translating the support along the operation table side-guides. For additional orientation the instrument guiding system can be turned around the perpendicular axis of the support guide and fixed manually.

A similar approach using a four-bar-linkage for endoscope guidance has been reported by J. Funda [Funda 94]. This approach provides four degrees of freedom of motion for endoscope and instrument guidance. The surgical robot is standing on the floor. If the operation table and the patient move, an adjustment of the location of the remote center of motion will become necessary.

The manipulator shown in Fig. 6 enables large ranges of motion around the incision point and is attached to the operation table. Thus, the adjusted location of the invariant point can remain constant during the entire endoscopic procedure, neglecting small, relative motions of the elastic abdominal wall. The articulated arm design and the horizontal, initial position of the instrument employed enable easy access to the operation table. The corresponding, prototypic master device is an identical kinematic structure. Instead of the effector, a handle is fixed to the endoscopic multi-link mechanism for motion control in the master-slave-mode. Integration into a universal master control concept is also intended [Holler 93].

5 Graphical Computer Simulation

With the development of endoscopic handling systems, surgeons face the problem of familiarization with completely new techniques and procedures. The presented endoscopic training interface is dedicated to the most important laparoscopic operations presently performed. The set-up enables following practical exercises:

- Coordination of different instruments under synthetic view
- Handling of an endoscope mock-up with its corresponding synthetic camera view
- Teamwork of surgeon, assistant and cameraman
- Simulation of new instrument designs and guiding systems for powered instruments and cameras
- Measurement of handling speeds in a simulated environment
- But also test of different master-arm configurations

The design concept of the Karlsruhe endoscopic surgery simulator [Kühnapfel 94] takes into account the cinematics of conventional endoscopic handling with four degrees of freedom. Furthermore it allows for future extension of the training interface for the dexterous instruments and guiding systems presented. It consists of a plastic phantom box with five inserted trocar tubes guiding four instrument- and one endoscope mock-up. The incision point in the abdomi-

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nal wall is considered to be a cardanic suspension of the trocar tube (Fig. 1) in the endoscopic trainer. The instrument's shaft can rotate around and slide along the trocar tube. Instead of using e.g. a polhemous tracker for the measurement of the absolute position and orientation of the instrument tip, a miniaturized guiding mechanism has been designed which measures the joint motions introduced in Fig. 1. Each motion axis is equipped with a precision potentiometer. The mechanisms provide an invariant point of motion in the 'points of incision' of the endoscopic training interface. The sensorized guiding mechanism enables the precise computation of the absolute position and orientation of the effector using the forward solution of endoscopic kinematics with four degrees of freedom. Commercially available instrument handles were connected with the endoscopic shafts. The instrument handles are equipped with potentiometers, in order to measure the gripping motion. The instrument mock-ups are interchangeable to allow different configurations of the surgical set-up. As indicated before, mock-ups of powered instruments equipped with switches and potentiometers for additional effector functions and motion axes can be also inserted into the endoscopic training interface.

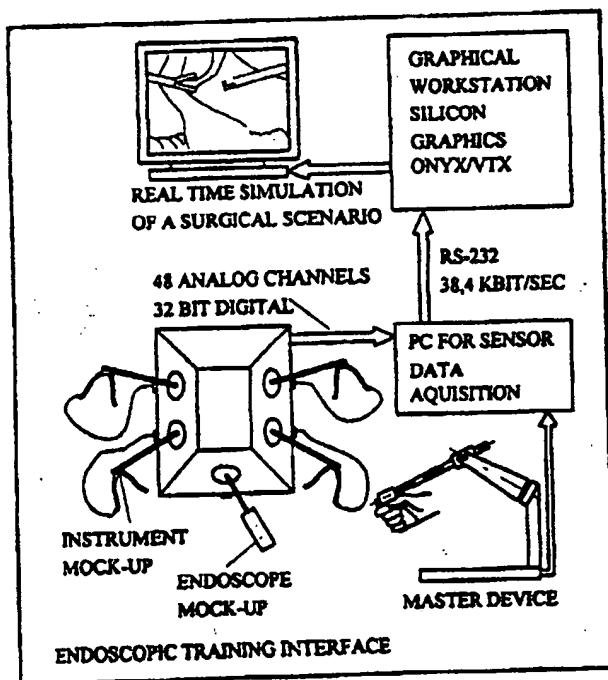


Fig 7: The Karlsruhe endoscopic simulator

The experimental set-up consists of the endoscopic training interface, a PC DX-386 for data acquisition and a graphical workstation. All measured joint and handle positions are transmitted by up to 48 analog channels with a resolution of 12 bit. Additional signals from switches are connected to a 32 bit digital I/O-board. On request of the graphical workstation the signals are submitted from the PC by a RS-

232 Interface with 38400 Baud. The KISMET-software (Kinematical Simulation and Monitoring Environment for Telerobotics) [Kühnapfel 93] allows a realtime master-slave-control of modelled instruments in their virtual operating environment. Instead of using miniaturized guiding mechanisms and instrument mock-ups inserted in the training interface, separate master devices can be connected to the data acquisition system and tested for a master-slave control in effector coordinates. Thus, the operators will have the opportunity to experience the control of the endoscopic handling system under development.

6 Safety Aspects

The concept of mechanically constrained motion guiding of endoscopic instruments around an invariant point has already been proved in surgical robotics [Davies 1992]. The cardanic axes of the laparoscopic telemanipulator are mechanically constrained and limited in their ranges of motion, thus providing inherent safety in endoscopic handling around the incision point in the abdominal wall. This is an essential advantage of the concept presented with a view to potential applications using industrial robots as instrument guiding system.

In first experiments a simplified, PC-based master-slave control based on a modular conception will be used. The control schemes of the decoupled motion axes will be optimized, avoiding overshoot and vibrations due to stick-slip effects. The inputs from the operator's hands to the master device have to be checked and filtered by an internal coordinator.

Also endoscopic handling forces must be also measured in order to supervise the operation. This can be done either by using a standard six-degrees-of-freedom force-torque sensor, placed between the instrument carrier and the carrier guides or by a miniaturized, endoscopic force-torque sensor behind the surgical effector. The coordinator checks the safety of handling based on these sensor inputs to avoid incorrect operation of the manipulator.

The effector functions are directly controlled by switches in the master handle and foot pedals currently used in surgery. After that first experimental program the endoscopic telemanipulator will be integrated in a KfK-telepresence system [Holler 1993]. In summary, the endoscopic master-slave-telemanipulator is immediately controlled by the decision the operator makes. Elements of artificial intelligence should, however, avoid dangerous mistakes during telemanipulator assisted surgery.

7 Conclusion

The presented, endoscopic telemanipulation concept of a powered dexterous instrument and an instrument guiding system is presently implemented. Besides the development of special kinematical structures, control schemes and safety

strategies, the optimization and integration of suitable surgical effectors is a key problem of efficient endoscopic telemanipulation. The effectors presented are essential components of a future endoscopic handling system. Experiments with functional prototypes of concept components carried out in cooperation with the University of Tübingen, have shown that they are suited to assist the surgeon.

Furthermore graphical computer simulations enable first interactive control of a computer model of the telemanipulator with a simple master device. Experience gained in simulated teleoperation will be taken into account, especially in the further development of safety features and of the man-machine interface. Advanced real time computer simulation shows interesting perspectives for surgical training and operation planning.

But surgical robotic systems which use individual patient data as a basis of automatic path planning and the execution of endoscopic operations neglect the flexibility of organs and the complexity of the unstructured environment. Thus, safety can only be guaranteed in case of relatively stiff structures which do not move. The endoscopic master-slave-telemanipulator is guided by the operator's decision and responsibility, thus enabling an efficient, intuitive handling of surgical effectors and cameras with six degrees of freedom inside the abdominal cavity.

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